Collider, direct and indirect detection of supersymmetric dark matter

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Abstract. We present an overview of supersymmetry searches, both at collider experiments and via searches for dark matter (DM). We focus on three DM possibilities in the SUSY context: the thermally produced neutralino, a mixture of axion and axino, and the gravitino, and compare and contrast signals that may be expected at colliders, in direct detection (DD) experiments searching of DM relics left over from the Big Bang, and indirect detection (ID) experiments designed to detect the products of DM annihilations within the solar interior or galactic halo. Detection of DM particles using multiple strategies provides complementary information that may shed light on the new physics associated with the dark matter sector. In contrast to the mSUGRA model where the measured cold DM relic density restricts us to special regions mostly on the edge of the $m_0 - m_{1/2}$ plane, the entire parameter plane becomes allowed if the universality assumption is relaxed in models with just one additional parameter. Then, thermally produced neutralinos with a well-tempered mix of wino, bino and higgsino components, or with a mass adjusted so that their annihilation in the early universe is Higgs-resonance-enhanced, can be the DM. Well-tempered neutralinos typically yield heightened rates for DD and ID experiments compared to generic predictions from minimal supergravity. If instead DM consists of axinos (possibly together with axions) or gravitinos, then there exists the possibility of detection of quasi-stable next-to-lightest SUSY particles at colliding beam experiments, with especially striking consequences if the NLSP is charged, but no DD or ID detection. The exception for mixed axion/axino DM is that DD of axions may be possible.

1. Introduction: dark matter in SUSY models

In the 1930's, the astronomer Fritz Zwicky noticed something was amiss in the universe[1]: observations of galactic clusters seemed in contradiction with the amount of luminous matter present in them. Specifically, they seemed to be lacking enough gravitational pull in order to maintain themselves as bound clusters. To account for the discrepancy without modifying the laws of gravity, Zwicky hypothesized that most of the mass of the galaxy was contained in non-luminous, or dark, matter (DM). Few paid attention to Zwicky's hypothesis until the 1970s, when Ford and Rubin, measuring the rotation curves of galaxies[2], found that stellar velocities did not drop-off with radial distance in accord with Newton's laws, but instead stayed high out to the largest distances accessible to observation. An explanation could be found by resuscitating Zwicky's DM conjecture.

In recent times, cosmology has entered a much more quantitative period, highlighted by: detailed measurements of anisotropies in the cosmic microwave background radiation[3], measurements of galactic lensing[4] and comparisons of large scale structure to n-body simulations of the development of structure in the universe[5]. All these measurements, when combined into a standard cosmological model, point decisively towards a universe constituted of 4% baryonic matter, along with $\sim 25\%$ cold dark matter, and about 70% dark energy (DE)[6]. A tiny fraction remains associated with electrons, neutrinos and photons. The accelerating Universe [7], and the concomitant DE, came as a surprise in the late 1990s. A cosmological constant was not unanticipated in theoretical cosmology, and an upper bound nearly equal to its measured value was obtained a decade earlier[8]. Although the origin of DE remains an outstanding puzzle, much mystery remains around the DM as well[9]. While the amount of DM in the universe is becoming ever-more precisely known, the identity of the particle (or particles) is completely unknown. What is known is that the bulk of the dark matter must be *cold*, *i.e.* non-relativistic particles with velocities so low they can clump, or become gravitational bound on large scales, thus providing the seeds for structure formation. This rules out active neutrinos as DM. Unraveling the nature of the cold dark matter (CDM) in the universe is one of the most exciting directions in scientific research today. Happily, a bevy of experiments currently operating, being deployed, or in the planning stage, promises rapid progress on uncovering the properties of CDM during the next few years.

None of the particles of the Standard Model (SM) of particle physics (which encapsulates the laws of physics as we know them) has the right properties to make up the CDM, calling for a major revision in our knowledge of the laws of physics. Indeed the SM is best viewed as an *effective field theory*, a set of laws that gives a valid description of nature *up to the weak interaction energy scale* $\sim 0.1 - 1$ TeV; it almost certainly breaks down beyond this scale, as evidenced by instabilities in the electroweak symmetry breaking sector of the theory.

On the cosmology side, if one assumes the existence of a DM particle that was in

thermal equilibrium early in the universe's history, and has not been produced after the Universe cooled below the DM particle mass, one can unambiguously calculate its relic abundance by solving its Boltzmann equation. The answer depends on the dark matter particle's annihilation cross section and mass. Remarkably, a DM particle with a weak scale mass and an annihilation cross section of weak interaction size yields about the observed relic density, strongly suggesting a *weakly interacting massive particle*, or WIMP, as the CDM candidate (though other possibilities also exist[10].). This is often pointed to as providing independent astrophysical evidence that new physics ought to exist at the weak scale, and is sometimes termed *the WIMP miracle*. The goal of the CERN Large Hadron Collider experiments – which will begin gathering data starting in late 2009 – is to make a thorough exploration for new matter states and interactions in and around the weak scale.

The theoretical literature is replete with candidate CDM particles. While some of these are postulated specifically to solve the CDM problem, others emerge as solutions to long-standing problems in particle physics. Examples of the latter include *axions*, which emerge from the Peccei-Quinn (PQ) solution to the strong CP problem[11], and WIMPs, that are frequently contained in particle physics theories that attempt to stabilize the weak scale. In this paper, we will focus upon dark matter candidates which emerge from particle physics models with *weak scale supersymmetry* (SUSY) [12]. In the Minimal Supersymmetric Standard Model (MSSM) with a conserved R-parity, the lightest SUSY particle (LSP) is absolutely stable. In many SUSY models, the LSP is the massive, electrically neutral, and weakly interacting lightest neutralino $\widetilde{Z}_1$, and thus an excellent WIMP candidate. If one includes the gravity multiplet – including the graviton and spin-$\frac{3}{2}$ gravitino states – then the gravitino $\tilde{G}$ is also a good CDM candidate. In this case, since $\tilde{G}$ only interacts gravitationally, it is usually termed a *superWIMP*[13]. Finally, in models where the PQ solution to the strong CP problem is invoked, spin-0 axions and their R-odd spin-$\frac{1}{2}$ partner *axinos* $\tilde{a}$ occur. In this case, both the axion[14] and axino[15] can account for the CDM. The axino is sometimes called an extremely weakly interacting massive particle, or *eWIMP* [16].‡ Weak scale SUSY models *i*). solve the hierarchy problem, *ii*). naturally accommodate CDM, and *iii*). automatically lead to the unification of the measured gauge couplings, a triple coincidence that seems hard to ignore.

If CDM is dominantly WIMPs, then it may be possible to produce and study the DM particle(s) directly at colliding beam experiments such as the CERN LHC. Direct production of DM particles is not likely to be visible above SM backgrounds at LHC. However, production of new matter states *associated with the DM*, and which decay into DM particles, often lead to robust new physics signatures. In such scenarios the LHC may then turn out to be a DM factory, where the nature of DM particles and their properties might be studied in a controlled environment. In a collider detector, WIMPs would be like neutrinos in that they would escape without depositing any energy in the

‡ A fourth SUSY CDM candidate, the right-handed sneutrino, is also possible: see Ref. [17] for further details.

experimental apparatus, resulting in an *apparent imbalance of energy and momentum* in collider events. While WIMPs would manifest themselves only as *missing (transverse) energy* in (hadron) collider experiments, it should nevertheless be possible to study the *visible* particles produced in WIMP-related production and decay processes to study the new physics associated with the WIMP sector.

Indeed, there exists a real possibility that the nature of WIMP DM and its associated new particle sector will be clarified in the next decade by a *variety* of experiments that are already operating, or are soon-to-be deployed. In this effort, experiments at the LHC will play a crucial role. There are – in tandem with the LHC – a variety of other dark matter search experiments already in operation, or in a deployment or planning phase. *Direct detection* (DD) experiments seek to directly measure relic DM particles left over from early stages of the Big Bang. These DD experiments range from terrestrial microwave cavities that search for axions via their conversion to photons, to crystalline or noble liquid targets located deep underground that allow for a search for WIMP-nucleon collisions by detecting the nuclear recoil.

DM may also be searched for in *indirect detection* (ID) experiments. In ID experiments, one searches for WIMP-WIMP annihilation into various SM particles including neutrinos, gamma rays and anti-matter. Clearly, this technique applies only if the DM is self-conjugate, or if DM particles and anti-particles are roughly equally abundant. One ID search method involves the use of neutrino telescopes mounted deep under water or in polar ice. The idea is that if relic WIMPs are the DM in our galactic halo, the sun (or earth) will sweep them up as it follows its galactic orbit. The WIMPs then become gravitationally trapped in the solar core where they can accumulate, essentially at rest, to densities much higher than in the Milky Way halo. These accumulated WIMPs can then annihilate one with another into SM particles with energies $E \lesssim m_{\rm WIMP}$. Most annihilation products would be immediately absorbed by the solar material. However, neutrinos produced as primaries or secondaries by WIMP annihilation, can easily escape the sun resulting in an isotropic flux of *high energy* neutrinos from the solar core, some of which would make it to earth. For $m_{\rm WIMP} \geq$ few GeV, the resulting neutrino energies are impossible to produce via conventional nuclear reactions in the sun. The neutrinos will occasionally interact with nuclei in ocean water or ice and convert to a high energy muon, which could then be detected via Cerenkov radiation by photomultiplier tubes located within the medium.

Another possibility for ID is to search for the by-products of WIMP annihilation in various regions of our galactic halo. Even though the halo number density of WIMPs would be quite low, the volume of the galaxy is enormous, and one can look for rare anti-matter production or high energy gamma ray production from these WIMP halo annihilations. A variety of land-based, high altitude and space-based anti-matter and gamma ray detectors have been or are being deployed. The space-based Pamela experiment is searching for positrons and anti-protons. The land-based HESS telescope has recently been joined by the Fermi Gamma-ray Space Telescope (FGST) in the search for high energy gamma rays. While high energy anti-particles would provide

a striking signal, these lose energy upon deflection when traversing the complicated galactic magnetic field, and so can only be detected over limited distances. Gamma rays, on the other hand, are undeflected by magnetic fields, and so have an enormous range and, furthermore, point back to their source. Thus, the galactic center, where dark matter is expected to accumulate at a high density, might be a good source of GeV-scale gamma rays resulting from WIMP-WIMP annihilation to vector boson ($V = W, Z$) pairs or to quark jets, followed by $(V \rightarrow) q \rightarrow \pi^0 \rightarrow \gamma\gamma$ after hadronization and decay.

If WIMPs and their associated particles are discovered at the LHC and/or at DD or ID search experiments, it will be a revolutionary discovery. But it will only be the beginning of the story as it will usher in a new era of *dark matter astronomy.* The next logical step would be the construction of an e^+e^- collider of sufficient energy so that WIMP (and related particles) can be produced and studied with high precision in a clean, well-controlled experimental environment. The precise determination of particle physics quantities associated with WIMP physics can allow us to *deduce* the expected WIMP relic density within the standard Big Bang cosmology. If this turns out to be in agreement with the measured relic density, we would have direct evidence that DM consists of a single component. If the predicted relic density is too small, it could make the case for multiple components in the DM sector. If the predicted density is too large, we would be forced to abandon the simplest picture and seek more complicated (non-thermal) mechanisms to account for the measurement. In this case, we would also be able to deduce that the detected WIMP is itself unstable, and that the DM is perhaps some lighter decay product. The determination of the properties of the DM sector will also serve as a tool for a detailed measurement of astrophysical quantities such as the galactic and local WIMP density and local velocity profiles, which could shed light on the formation of galaxies and on the evolution of the universe.

2. Neutralino dark matter in gravity-mediated SUSY breaking models

Even with the assumption of R-parity conservation, the MSSM has a very large number of parameters making phenomenological analyses intractable. It is customary to make assumptions based on physical insight as to how SUSY breaking effects are communicated from the SUSY breaking sector to the SM superpartners. This has led to the development of simple models, each with just a handful of parameters, characterized by the mediation-mechanism for SUSY breaking, and with distinct predictions for the masses and couplings of sparticles. While these various models can all accommodate the observed relic density, gravity-mediated SUSY breaking models lead to thermal WIMP dark matter in the most natural way, and hence are the focus of our attention.

Once a SUSY model is specified, then given a set of input parameters, it is possible to compute all superpartner masses and couplings necessary for phenomenology. We can then use these to calculate scattering cross sections and sparticle decay modes to evaluate SUSY signals (and compare against corresponding SM backgrounds) in collider experiments. We can also check whether the model is allowed or excluded

by experimental constraints, either from direct SUSY searches, *e.g.* at LEP2 which requires that $m_{\widetilde{W}_1} > 103.5$ GeV, $m_{\tilde{e}} \gtrsim 100$ GeV, and $m_h > 114.4$ GeV (for a SM-like light SUSY Higgs boson h), or from indirect searches through loop effects from SUSY particles in low energy measurements such as $BF(b \to s\gamma)$ or $(g-2)_\mu$. We can also calculate the expected lightest neutralino relic density $\Omega_{\widetilde{Z}_1} h^2$, assuming $\widetilde{Z}_1$ is the LSP, or for that matter any other stable particle in the theory. For the sparticle mass spectrum, we adopt the Isasugra subprogram of Isajet[18], while for the neutralino relic density calculation, we adopt the IsaReD[19] subprogram; the latter includes all relevant neutralino annihilation and co-annihilation reactions.

2.1. The mSUGRA model

The minimal supergravity model (mSUGRA)[20]§ is a prototypical model for investigations of the phenomenological consequences of weak scale supersymmetry. The parameter space of the model is given by

$$m_0,\ m_{1/2},\ A_0,\ \tan\beta,\ sign(\mu), \tag{1}$$

where m_0 is a common GUT scale soft SUSY breaking (SSB) scalar mass, $m_{1/2}$ is a common GUT scale SSB gaugino mass, A_0 is a common GUT scale trilinear SSB term, $\tan\beta$ is the ratio of Higgs field vevs, and μ is the superpotential Higgs mass term, whose magnitude, but not sign, is constrained by the electroweak symmetry breaking minimization conditions.

To illustrate how various theoretical and experimental constraints constrain the parameter space of the mSUGRA model, we show in Fig. 1 the m_0 *vs.* $m_{1/2}$ plane, where we take $A_0 = 0$, $\mu > 0$ and $\tan\beta = 10$ for three different values of m_t. The red-shaded regions are not allowed because either the $\tilde{\tau}_1$ becomes the lightest SUSY particle, in contradiction to negative searches for long lived, charged relics (left edge), or EWSB is not correctly obtained (lower-right region). The blue-shaded region is excluded by LEP2 searches for chargino pair production ($m_{\widetilde{W}_1} < 103.5$ GeV). Below the magenta contour near $m_{1/2} \sim 300$ GeV, $m_h < 110$ GeV, which is roughly the LEP2 lower limit on m_h in the model. The thin green regions at the boundary of the unshaded white region has $0.094 < \Omega_{\widetilde{Z}_1} h^2 < 0.129$ where the neutralino saturates the observed relic density. In the adjoining yellow regions, $\Omega_{\widetilde{Z}_1} h^2 < 0.094$, so these regions require multiple DM components. The white regions all have $\Omega_{\widetilde{Z}_1} h^2 > 0.129$ and so give too much thermal DM: they are excluded in the standard Big Bang cosmology unless the neutralino decays either via small R-parity violating couplings, or the model is extended to include yet lighter sparticles.‖ For the reader's convenience, we also show contours of constant gluino and first generation squark mass, which are useful for understanding the SUSY reach of the LHC.

The DM-allowed regions are classified as follows:

§ This is often also referred to as the constrained MSSM, or CMSSM, in the literature.
‖ For non-standard cosmology, then all bets are off [21].

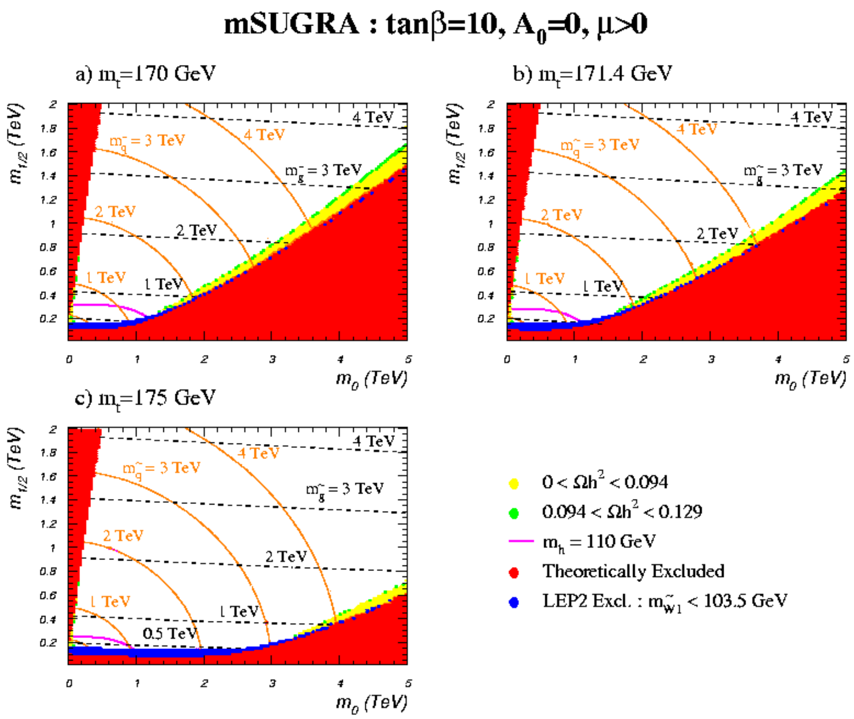

Figure 1. *The m_0 vs. $m_{1/2}$ plane in mSUGRA for $A_0 = 0$, $\tan\beta = 10$ with $\mu > 0$ and a) $m_t = 170$ GeV, b) $m_t = 171.4$ GeV and c) $m_t = 175$ GeV. The red-shaded regions are excluded because electroweak symmetry is not correctly broken, or because the LSP is charged. Blue regions are excluded by direct SUSY searches at LEP2. Yellow and green shaded regions are WMAP-allowed, while white regions are excluded owing to $\Omega_{\widetilde{Z}_1} h^2 > 0.129$. Also shown are gluino and first generation squark mass contours, as well as a magenta contour below which $m_h \leq 110$ GeV.*

- At very low m_0 and low $m_{1/2}$ values is the so-called *bulk* annihilation region[22]. Here, sleptons are quite light, so $\widetilde{Z}_1\widetilde{Z}_1 \to \ell\bar{\ell}$ via t-channel slepton exchange is the dominant neutralino annihilation process in the early universe.
- At low m_0 and moderate $m_{1/2}$, there is a thin strip of allowed region adjacent to the stau-LSP region where the neutralino and the lighter stau were in thermal equilibrium in the early universe. Here, neutralino co-annihilation with the light stau serves to bring the neutralino relic density down to its observed value[23].
- At large m_0, adjacent to the EWSB excluded region on the right, is the hyperbolic branch/focus point (HB/FP) region, where the superpotential μ parameter becomes small and the higgsino-content of $\widetilde{Z}_1$ increases significantly. Then $\widetilde{Z}_1$ becomes mixed higgsino-bino dark matter (MHDM) and can annihilate efficiently via the gauge coupling to its higgsino component. If $m_{\widetilde{Z}_1} > M_W$ and M_Z, then $\widetilde{Z}_1\widetilde{Z}_1 \to WW,\ ZZ,\ Zh$ is enhanced, and one finds the correct measured relic density[24]. Deep in the HB/FP region, co-annihilation with the (higgsino-like) $\widetilde{W}_1$ and $\widetilde{Z}_2$ can be important.

If the parameter $\tan\beta$ is increased much beyond 10, then bottom and tau Yukawa couplings become large, and the value of m_A steadily drops. The situation is depicted in Fig. 2, where we show the mSUGRA m_0 *vs.* $m_{1/2}$ plane for increasing values of $\tan\beta$.

- For $\tan\beta \sim 45-55$, the value of m_A is small enough so that $\widetilde{Z}_1\widetilde{Z}_1$ can annihilate into $b\bar{b}$ pairs through the s-channel A (and also H) resonance. This region has been dubbed the A-funnel[25]. It can be quite broad at large $\tan\beta$ because the width Γ_A becomes very wide due to the large b- and τ- Yukawa couplings.
- It is also possible at low $m_{1/2}$ values that a light Higgs h resonance annihilation region can occur just above the LEP2 excluded region[26].
- Finally, if A_0 is large and negative, then the $\tilde{t}_1$ can become light. If $m_{\tilde{t}_1} \sim m_{\widetilde{Z}_1}$, then stop-neutralino co-annihilation[27] can occur.

Bino-wino coannihilation, which is possible in extended models discussed below, is not possible in this model on account of the assumed unification of gaugino mass parameters.

2.2. Direct and indirect detection of neutralino DM

Since it is possible relic WIMPs are still annihilating in our Galactic halo, the ID detection rates mentioned in Sec. 1 depend on the assumed galactic DM density (halo) profile. We show several popular halo profiles in Fig. 3. Most models are in near accord at the earth's position at ~ 8 kpc from the galactic center. However, we see that predictions for the DM density near the galactic center differ wildly, which translates to large uncertainties for DM annihilation rates near the galactic core. The corresponding uncertainty will be smaller for anti-protons, and smaller still for positrons, since these particles gradually lose energy while propagating through the galaxy, and so can reach us from limited distances over which the halo density is relatively well-known. Possible clumping of DM yields an additional source of uncertainty in ID detection rates.

DD rates are determined by the local DM density (usually taken to be $\rho_{local} \simeq 0.3$ GeV/cm^3), the WIMP mass and the WIMP-nucleon scattering cross section. Most experiments are sensitive mainly to the *spin-independent* WIMP-nucleon cross section, since in this case WIMP scattering rates are $\propto A^2$ (where A is the mass number of the nuclear target) because the WIMP here couples *coherently* to the entire nucleus: hence its scattering cross section is amplified for heavy nuclei.

We have calculated the cross section $\sigma_{\rm SI}(\widetilde{Z}_1 p)$ via the scalar interaction using the program IsaReS[28]. We show some results from the mSUGRA model in Fig. 4a), where we fix mSUGRA parameters $m_{1/2} = 1$ TeV, $A_0 = 0$ and $\tan\beta = 55$. We plot the cross section against variation in m_0. At low $m_0 \sim 700$ GeV, we are in the stau co-annihilation region, and the $\widetilde{Z}_1$ is nearly bino-like. Here, the DD rates are well below the projected sensitivity of the Xenon-100 or LUX experiments, depicted by the dotted line, which shows the sensitivity for a 100 GeV neutralino. (For a bino-like neutralino with a mass ~ 400 GeV that obtains for $m_0 \lesssim 2$ TeV, the detectability level is about twice this.) As m_0 steadily increases, $m_{\widetilde{Z}_1}$ changes only slowly until the magnitude of the μ

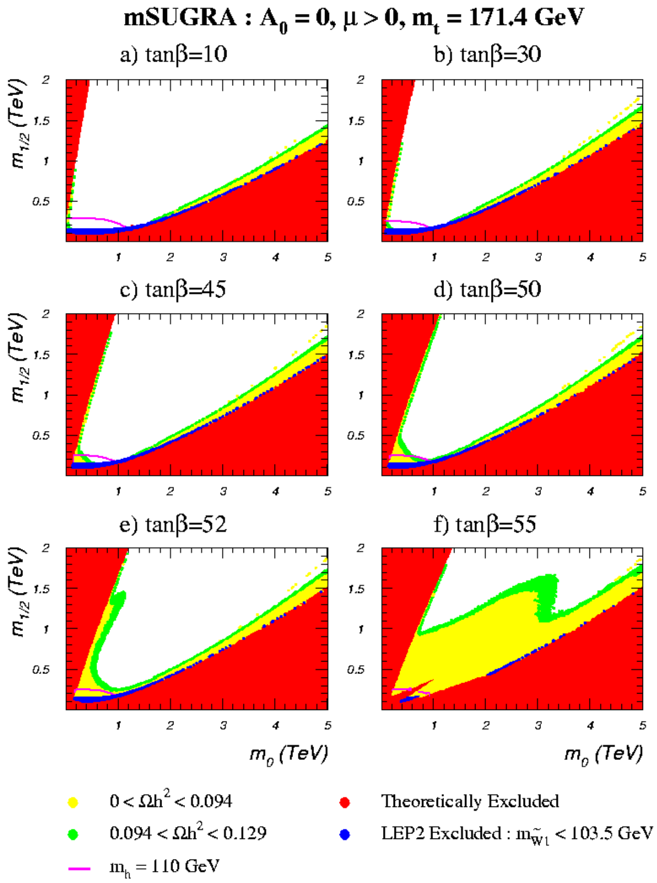

Figure 2. *The m_0 vs. $m_{1/2}$ plane in mSUGRA for $A_0 = 0$ and various values of $\tan\beta$, with $\mu > 0$ and $m_t = 171.4$ GeV. The red-shaded regions are excluded because electroweak symmetry is not correctly broken, or because the LSP is charged. Blue regions are excluded by direct SUSY searches at LEP2. Yellow and green shaded regions are WMAP-allowed, while white regions are excluded owing to $\Omega_{\widetilde{Z}_1}h^2 > 0.129$. Below the magenta contour in each frame, $m_h < 110$ GeV.*

parameter drops to sufficiently low values and the $\widetilde{Z}_1$ becomes increasingly higgsino-like. The $\widetilde{Z}_1$ coupling to Higgs bosons increases, as does $\sigma_{\rm SI}(\widetilde{Z}_1 p)$. In the HB/FP region, the cross section reaches above the 10^{-8} pb level, within the reach of the next round of experiments.

In Fig. 4*b*), we show the flux of muons from $\nu_\mu \to \mu$ conversions at earth coming from neutralino annihilation to SM particles within the solar core. Here, we use the Isajet/DarkSUSY interface for our calculations[29], and require $E_\mu > 50$ GeV. The predicted rate depends in this case mainly on the sun's ability to sweep up and capture neutralinos, which depends mainly on the *spin-dependent* neutralino-nucleon scattering cross section (since in this case, the neutralinos mainly scatter from solar Hydrogen, and there is no mass number enhancement), mostly sensitive to Z exchange. The rates

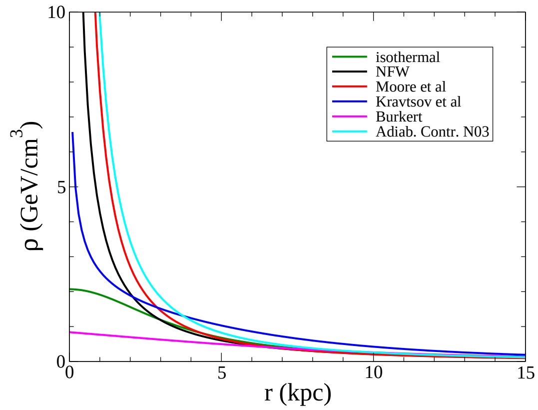

Figure 3. *Several galactic dark matter halo density profiles. Notice that while these differ greatly close to the core of our Galaxy, they agree at the location of the sun, about 8 kpc from the Galactic center.*

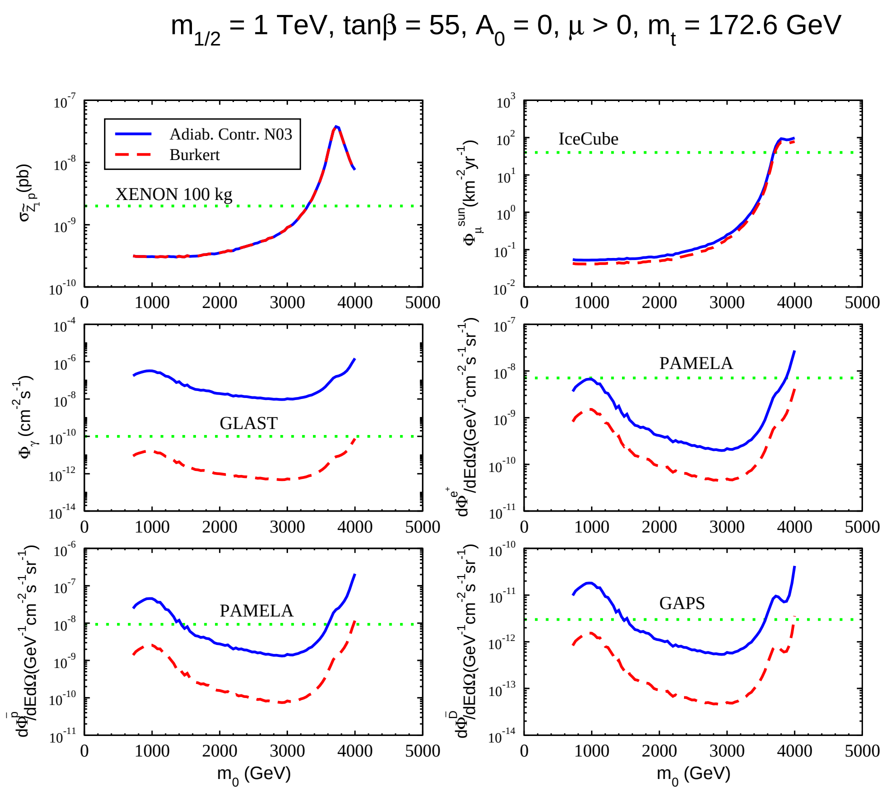

Figure 4. *Projected rates for direct and indirect detection of neutralino dark matter in mSUGRA model for the Burkert and Adiabatically contracted N03 halo profiles, with mSUGRA parameters as listed. Also shown are expected sensitivities of various experiments.*

are again low for low m_0 with bino-like neutralinos, but reach the IceCube detectability level at large m_0 in the HB/FP region where neutralino couplings to Z become large.

In Fig. 4*c*), we show the expected flux of gamma rays with $E_\gamma > 1$ GeV, as required for the Fermi Gamma-ray Space Telescope (FGST), arising from DM annihilations in the galactic core. In this case, we see enhanced signal at both low m_0 and high m_0. The low m_0 enhancement occurs because we are at high $\tan\beta = 55$, and neutralinos can annihilate efficiently through the A-resonance since here $2m_{\widetilde{Z}_1} \sim m_A$[30]. As we move to higher m_0, m_A increases, and we move out of the A funnel. At very large m_0, we are back to the HB/FP region, and $\widetilde{Z}_1\widetilde{Z}_1 \to WW$, ZZ and $t\bar{t}$ are all enhanced, and we get elevated gamma ray detection rates. The predictions for two halo profiles differ by four orders of magnitude, reflecting the large uncertainty in our knowledge of the DM density at the center of our Galaxy.

In Fig. 4*d*)-*f*)., we show the expected flux of positrons, $\bar{p}$s and antideuterons $\overline{D}$ from neutralino halo annihilations.¶ Each of these frames show elevated rates in the A-funnel and in the HB/FP region. The various rates shown in this figure exemplify the possibility of a discrimination between DM annihilation mechanisms in the early universe[30]. If we are in the stau co-annihilation region, we expect very low rates for both DD and ID experiments, possibly with characteristic implications for the LHC [32]. In the A-funnel, we expect low rates for DD and ID via ν_μ telescopes, but enhanced rates for ID via gamma and anti-matter searches. If we are in the HB/FP region, then DD, ID via muons and ID via halo annihilations would all expect to be elevated, and possibly observable.

2.3. Dark matter at colliders: reach plots

In Fig. 5, we show the SUSY reach of various experiments in the $m_0 - m_{1/2}$ plane of the mSUGRA model for a low (left frame) and high (right frame) value of $\tan\beta$. The approximate SUSY reach of the LHC, assuming an integrated luminosity of 100 fb^{-1}, and of the proposed e^+e^- International Linear Collider operating at $\sqrt{s} = 0.5$ or 1 TeV are depicted by the correspondingly labelled contours. The LHC reach contour is a *cumulative* contour, but the largest reach appears in the inclusive multi-jet $+E_T^{\rm miss}$ channel[33]. In much of the accessible parameter space, signals in several different event topologies with differing numbers of hard, isolated leptons should be visible as well. This will help add confidence that one is actually seeing new physics, and may help to sort out the production and decay mechanisms. The reach at low m_0 extends to $m_{1/2} \sim 1400$ GeV. This corresponds to a reach for $m_{\tilde{q}} \sim m_{\tilde{g}} \sim 3.1$ TeV. At large m_0, squarks and sleptons are in the $4 - 5$ TeV range, and are too heavy to be produced at significant rates at LHC. Here, the reach comes mainly from just gluino pair production.

¶ Several groups [31] have recently noted that positrons (but not anti-protons or anti-deuterons) with energies up to $\mathcal{O}(100)$ GeV can be produced in local pulsars. It will be essential to understand the level of this pulsar background to any positron signal from annihilating DM. It would be also interesting to study whether collisions of protons, accelerated by the same mechanism as positrons, with matter in the environment can produce a detectable flux of high energy neutrinos pointing back to the pulsar.

In this range, the LHC reach is up to $m_{1/2} \sim 700$ GeV, corresponding to a reach in $m_{\tilde{g}}$ of about 1.8 TeV, and may be extended by $\sim$ 15-20% by b-jet tagging[34]. While LHC can cover the relic density allowed bulk and stau co-annihilation regions, as well as most of the A-funnel region that appears only for large $\tan\beta$, the HB/FP region extends far beyond the LHC reach. The ILC(1000) reach is everywhere lower than LHC, except in the HB/FP region. In this region, while gluinos and squarks can be extremely heavy, the μ parameter is small, leading to a relatively light spectrum of charginos and neutralinos. These are not detectable at the LHC because the visible decay products are too soft. However, with specialized cuts, chargino pair production is detectable at ILC even if the energy release in chargino decays is small, and the ILC reach extends beyond LHC in this region[35].

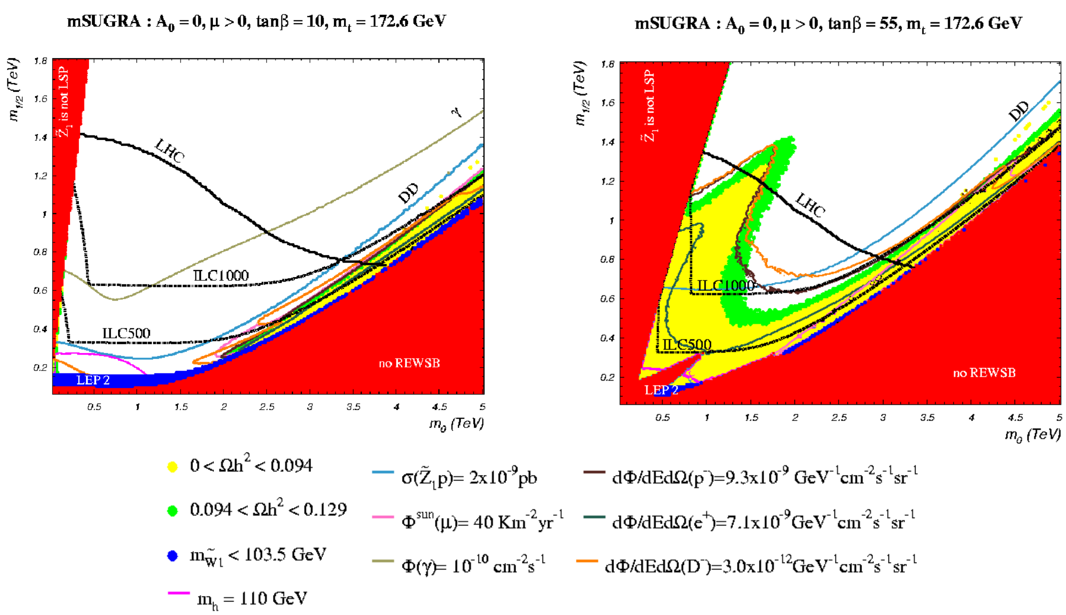

Figure 5. *The projected reach of various colliders, direct and indirect dark matter search experiments in the m_0 vs. $m_{1/2}$ plane of the mSUGRA model for $A_0 = 0$, $\mu > 0$, $m_t = 172.6$ GeV for $\tan\beta = 10$ (left frame) and $\tan\beta = 55$ (right frame). The DD and various ID contours are for the corresponding expected sensitivity in Fig. 4. For the ID results, we have adopted the N03 DM halo density profile.*

In Fig. 5, we also show reach contours for DD and ID searches for WIMP dark matter[30]. Signals from DD are observable in *i*). the region of low m_0 and low $m_{1/2}$, where squarks are light and scattering via squark exchange occurs, and *ii*). also in the *entire* HB/FP region (where $\tilde{Z}_1$ is MHDM) where the reach of the LHC is limited to $m_{1/2} \lesssim 700$ GeV. Thus, in the HB/FP region with $m_{1/2} > 700$ GeV, it is possible a DM direct detection signal might be seen, while no signal is evident from LHC. The DD rate increases with $\tan\beta$, accounting for the shift in the corresponding contour in the right hand frame.

The ν_μ rates at IceCube/Antares are largest in the HB/FP region, where spin-dependent scattering cross sections are large. For the peaked N03 halo profile used here, the γ signal is observable over a large part (the entire) plane in the left (right) frame, though we caution that this is very sensitive to the assumed profile. The expected $\bar{p}$ and $\overline{D}$ signals are large in the HB/FP region, and also cover much of the A-funnel in the right-hand frame, while positron signals are observable over a smaller region. For $\mu < 0$ and large $\tan\beta$, A is lighter than for $\mu > 0$, and the A-funnel extends well beyond the reach of the LHC; again, for this halo profile, ID anti-particle signals cover much of the A-funnel region.

2.4. Characterizing dark matter at collider experiments

SUSY discovery will undoubtedly be followed by a program to reconstruct sparticle masses, couplings and quantum numbers. What will we be able to say about dark matter in light of these measurements? Several groups have made such studies [36]. Baltz *et al.* examined four mSUGRA case study points (one each in the bulk region, the HB/FP region, the stau co-anihilation region and the A-funnel region). They extract from other studies the precision with which various sparticle properties could be measured at LHC, and also at a $\sqrt{s} = 0.5$ and 1 TeV e^+e^- collider. They then adopted a 24-parameter version of the MSSM, fit its parameters to these projected measurements, and used the result to predict several quantities relevant to astrophysics and cosmology: the dark matter relic density $\Omega_{\widetilde{Z}_1}h^2$, the spin-independent neutralino-nucleon scattering cross section $\sigma_{SI}(\widetilde{Z}_1 p)$, and the neutralino annihilation cross section times relative velocity, in the limit that $v \to 0$: $\langle\sigma v\rangle|_{v\to 0}$. This last quantity is the crucial particle physics input for estimating signal strength from neutralino annihilation to anti-matter or gammas in the galactic halo. What this yields then is a *collider measurement* of these key dark matter quantities. Arnowitt *et al.* [32] performed detailed studies of mSUGRA points in the stau co-annihilation region to project the precision with which LHC can "measure" the neutralino relic density.

As an illustration, we show in Fig. 6 (taken from Baltz *et al.* [36]) the precision with which the neutralino relic density is constrained by collider measurements for the LCC2 point which is in the HB/FP region of the mSUGRA model. Measurements at the LHC cannot fix the $\widetilde{Z}_1$ composition, and so are unable to resolve the degeneracy between a wino-LSP solution (which gives a tiny relic density) and the true solution with MHDM. Determinations of chargino production cross sections at the ILC can easily resolve the difference. It is nonetheless striking that up to this degeneracy ambiguity, experiments at the LHC can pin down the relic density to within $\sim 50\%$ (a remarkable result, given that there are sensible models where the predicted relic density may differ by orders of magnitude!). This improves to 10-20% if we can combine LHC and ILC measurements.

A collider determination of the relic density is very important. If it agrees with the cosmological measurement it would establish that the DM is dominantly thermal

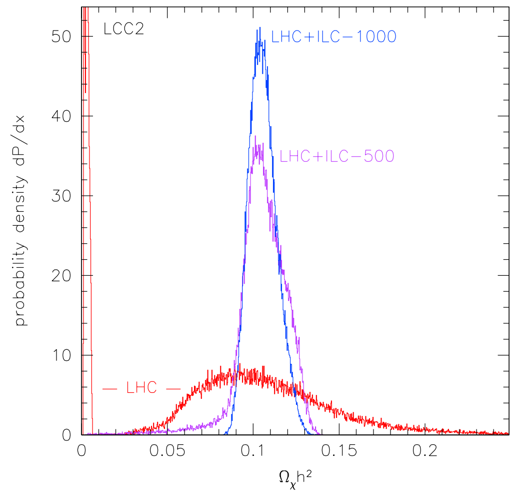

Figure 6. *Determination of neutralino relic abundance via measurements at the LHC and ILC, taken from Baltz et al. [36].*

neutralinos from the Big Bang. If the neutralino relic density from colliders falls significantly below the measured CDM density, it would provide direct evidence for multi-component DM– perhaps neutralinos plus axions or other exotica. Alternatively, if the collider determination gives a much larger value of $\Omega_{\widetilde{Z}_1}h^2$, it could point to a long-lived but unstable neutralino and/or non-thermal DM.

The collider determination of model parameters would also pin down the neutralino-nucleon scattering cross section. Then if a WIMP signal is actually observed in DD experiments, one might be able to determine the local DM density of neutralinos and aspects of their velocity distribution based on the DD signal rate. This density should agree with that obtained from astrophysics if the DM in our Galaxy is comprised only of neutralinos.

Finally, a collider determination of $\langle\sigma v\rangle|_{v\to 0}$ would eliminate uncertainty on the particle physics side of projections for any ID signal from annihilation of neutralinos in the galactic halo. Thus, the observation of a gamma ray and/or anti-matter signal from neutralino halo annihilations would facilitate the determination of the galactic dark matter density profile.

2.5. Non-universal SUGRA models: the well-tempered neutralino

The underlying universality of scalar mSUGRA parameters results from a technical assumption and so has a rather weak theoretical motivation [37]. Unification of gaugino mass parameters may also not obtain even in SUSY GUT models if the order parameter for SUSY breaking also breaks the GUT symmetry [38]. It is, therefore, of interest to consider models with non-universal SSB parameters.

In Fig. 7, we show the spin-independent $\widetilde{Z}_1 p$ cross section versus $m_{\widetilde{Z}_1}$ for a large number of one-parameter extensions of mSUGRA, where the GUT scale universality

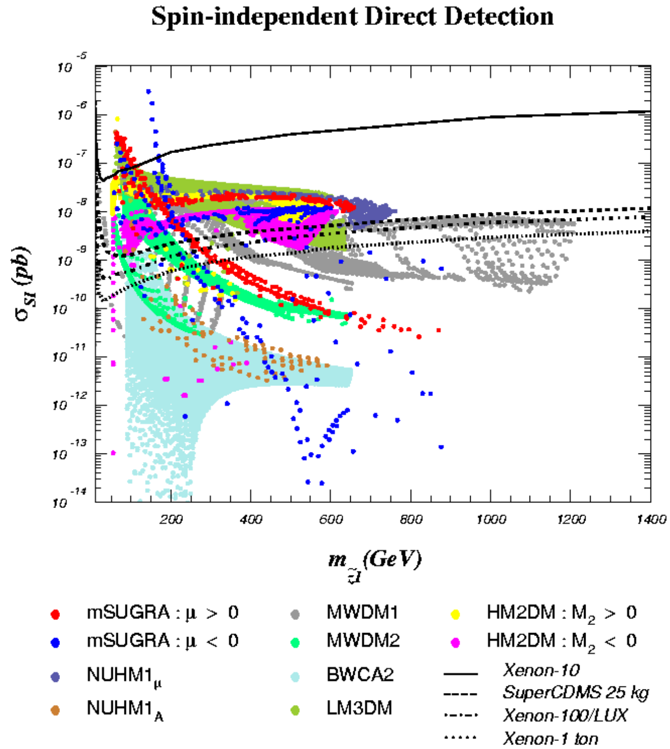

Figure 7. *The spin-independent neutralino-proton scattering cross-section vs $m_{\widetilde{Z}_1}$ in a variety of SUSY models, compatible with collider constraints where thermally produced Big Bang neutralinos saturate the observed dark matter density.*

between matter scalar and Higgs scalar mass parameters, or between the three gaugino mass parameters is relaxed in a systematic way. The details of the various models are not essential for our present purpose, but may be found in Ref. [39]. In each such model, shown by a different colour on the plot, this additional parameter is adjusted so that the lightest neutralino (assumed to be the LSP) *saturates* the observed relic abundance of CDM. We also include the mSUGRA model. To make this plot, we randomly generated points in the parameter space for each model, and plotted it on the figure if all current collider constraints on sparticle masses are satisfied. We also show the sensitivity of current experiments together with projected sensitivity of proposed searches at superCDMS, Xenon-100, LUX, WARP and at a ton-sized noble liquid detector. The key feature to note is that while the various models have a branch where $\sigma_{\rm SI}(p\widetilde{Z}_1)$ falls off with $m_{\widetilde{Z}_1}$, there is another branch where this cross-section asymptotes to $\sim 10^{-8}$ pb[40, 39, 41]. This branch (which includes the HB/FP region of mSUGRA) includes *many* models with MHDM which easily accommodate the measured relic density via *tempering* of the neutralino's higgsino content. In these cases, the spin-independent DD amplitude – which is mostly determined by the Higgs

boson-higgsino-gaugino coupling – is large because the neutralino has both gaugino and higgsino components. The exciting thing is that the experiments currently being deployed– such as Xenon-100, LUX, WARP and superCDMS – will have the necessary sensitivity to probe this *entire class of models*! To go further will require ton-size or larger detectors.

We note here that if $m_{\rm WIMP} \lesssim 150$ GeV, then it may be possible to extract the WIMP mass by measuring the energy spectrum of the recoiling nuclear targets[42]. Typically, of order 100 or more events are needed for such a determination to 10-20%. For higher WIMP masses, the recoil energy spectrum varies little, and WIMP mass extraction is much more difficult. Since the energy transfer from the WIMP to a nucleus is maximized when the two have the same mass, DD experiments with several target nuclei with a wide range of masses would facilitate the distinction between somewhat light and relatively heavy WIMPs, and so potentially serve to establish the existence of multiple WIMP components in our halo.

Before closing this section, we remark that in the various one-parameter extensions of mSUGRA that we have considered, *any point* in the $m_0 - m_{1/2}$ plane can be made consistent with the measured relic density. We therefore caution drawing inferences about collider signals from the relic density measurement from any analysis based on just the mSUGRA framework. Based on the analysis of the various one-parameter extensions of mSUGRA that we have studied [39], we infer that in most relic-density-consistent models: 1) $m_{\tilde{q}} \sim m_{\tilde{g}}$ so that the LHC reach extends to about $m_{\tilde{g}} \sim 3$ TeV, 2) $m_{\widetilde{Z}_2} - m_{\widetilde{Z}_1} < M_Z$, so that there should be a discernable edge in the opposite-sign, same-flavour dilepton mass distribution in SUSY events that can serve as a starting point for sparticle mass reconstruction at the LHC, 3) the mechanism that increases the neutralino annihilation rate frequently also enhances the direct or indirect rates for DM searches. In this connection, we remark that inclusion of neutrino Yukawa couplings as given by a $SO(10)$ SUSY GUT see-saw, significantly changes the location of the relic-density-consistent region in SUSY parameter space, but has little impact on the DD and ID detection rates [43].

3. WIMP signals in cosmic ray data?

Various indirect searches for DM have *already* turned up suggestive hints of a possible WIMP signal. These include:

- The HEAT experiment, in balloon flights from 1994, 1995 and 2000, measured an excess of positrons in cosmic ray data with energies in the range 10-30 GeV. Their measured rate is above that expected from WIMP dark matter annihilations, unless a substantial "boost" factor (enhancement due to fluctuations in the dark matter density distribution) of order 50 is included in the theoretical projections[44]. However, it now seems likely that they are seeing the influence of cosmic *protons*– rather than positrons– which actually ought to manifest themselves at high energy.

- The EGRET GeV anomaly: Here, a detection of an excess of around 0.5-5 GeV γ rays above background projections has been interpreted as possible WIMP annihilation into $b\bar{b}$ states[45]. This interpretation requires ring-like structures in the Miky Way DM density profile, along with galactic magnetic fields that sweep anti-protons out of the galactic disk. Although an interpretation[46] in terms of the mSUGRA model seems to contradict DD search limits from Xenon-10 and CDMS2, assuming a standard local DM density, the data can be accommodated by models with non-universal Higgs mass parameters [47]. However, it recently appears that the latest FGST data are *in accord* with background expectations[48], which may end up ruling out this galactic EGRET anomaly.
- The multi-GeV extra-galactic gamma ray anomaly, suggested by the EGRET observation of an apparent excess 1-20 GeV gamma rays has been interpreted as annihilation of a 500 GeV WIMP, and requires cuspy DM profiles in other galaxies which are not seen in the Milky Way[49].
- The WMAP collaboration measures an excess of microwave emissions from the galactic core. It has been suggested that WIMP annihilation in the galactic core into e^+e^- pairs, with subsequent synchroton emissions, could explain this WMAP Haze[50]
- Several particle physics explanations have been suggested to account for the excess of positrons with $E_{e^+} \sim 10 - 100$ GeV claimed by the Pamela collaboration [51], and the excess of electrons and/or positrons with $E_{e^\pm} \sim 300 - 800$ GeV claimed by the ATIC balloon experiment [52]. The explanations, which do not accommodate the possible structure seen in the ATIC energy spectrum, are also constrained by the fact that the measured $\bar{p}$ flux is consistent with SM predictions. Questions have also been raised as to just how well Pamela can discriminate *protons* from e^+s. Also, as noted in an earlier footnote, it appears possible to accommodate the claimed Pamela/ATIC signals in terms of acceleration of positrons produced via $\gamma\gamma \to e^+e^-$ in nearby pulsars [31]; this explanation naturally accounts for the non-observation of an excess of high energy anti-protons.

4. Gravitinos

4.1. The gravitino problem

In gravity-mediated SUSY breaking models, gravitinos typically have weak scale masses and, because they only have tiny gravitational couplings, are usually assumed to be irrelevant for particle physics phenomenology. Despite their tiny coupling, they are not irrelevant for cosmology where we may have the *gravitino problem.* Though not the LSP, gravitinos – while not in thermal equilibrium– can be produced in the early universe via emission from particles that are in thermal equilibrium. These *thermally produced* gravitinos then decay with a lifetime which is very roughly $\tau \sim G/m_{\tilde{G}}^3$, typically well after Big Bang nucleosynthesis (BBN). The late-time injection of hadronic (and

electromagnetic) energy from these gravitino decays into the cosmic soup can again disrupt the successful predictions of BBN [53, 54]. The precise constraints depend on the gravitino mass, the re-heating temperature T_R of the universe after inflation, and to a smaller extent on the various sparticle masses and mixings. We illustrate this in Fig. 8 where the constraint on the gravitino mass is shown as a function of the re-heating temperature for a case study in the HB/FP region of the mSUGRA model. We see that it is possible to accommodate $m_{\tilde{G}} \lesssim 3$ TeV and avoid disruption of BBN if $T_R \lesssim 10^5$ GeV. Such a low re-heat temperature puts severe constraints on inflationary models, and also call for rather low temperature baryogenesis mechanisms[55].

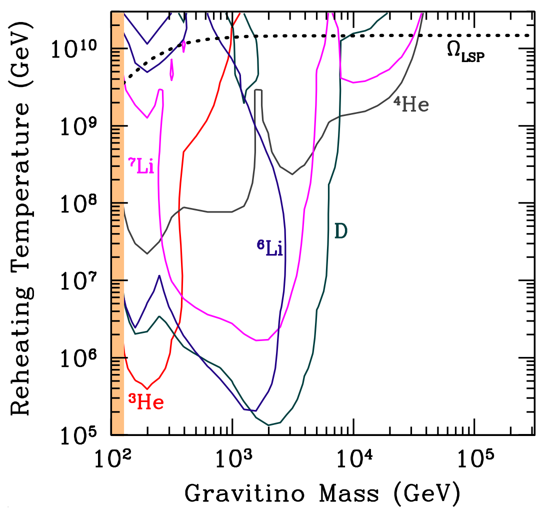

Figure 8. *An illustration of constraints from Big Bang nucleosynthesis which require T_R to be below the various curves, for the HB/FP region of the mSUGRA model with $m_0 = 2397$ GeV, $m_{1/2} = 300$ GeV, $A_0 = 0$ and* $\tan\beta = 30$*, from Ref. [54], to which we refer the reader for more details.*

Alternatively, we may assume that the massive $\tilde{G}$ is in fact the stable LSP, and thus constitutes the DM [56, 13]. In this case, one has to worry about thermal production of SUSY particles, followed by their late time decay in SM particles plus the gravitino since this may again disrupt the successful BBN predictions.

Finally, we remark here upon the interesting interplay of baryogenesis via leptogenesis with the nature of the LSP and the next-lightest-supersymmetric-particle (NLSP). For successful thermal leptogenesis to take place, it is found that the reheat temperature of the universe must exceed $\sim 10^9$ GeV[57]. If this is so, then gravitinos would be produced thermally with a huge abundance, and then decay late, destroying BBN predictions. For this reason, some adherents of leptogenesis tend to favor scenarios with a gravitino LSP, but with a stau NLSP[58]. A recent study [54] suggests that the gravitino LSP then has to be lighter than about 10 GeV unless $m_{\tilde{\tau}} > 1$ TeV, implying a very heavy sparticle spectrum.

4.2. Gravitinos as dark matter

Here, we consider the consequences of a gravitino LSP in SUGRA models[13, 59]. If gravitinos are produced in the pre-inflation epoch, then their number density will be diluted away during inflation. After the universe inflates, it enters a re-heating period wherein all particles can be thermally produced. However, the couplings of the gravitino are so weak that though gravitinos can be produced by particles in thermal equilibrium, gravitinos themselves never attain thermal equilibrium: indeed their density is so low that gravitino annihilation processes can be neglected in the calculation of their relic density. The thermal production (TP) of gravitinos in the early universe has been calculated and, including EW contributions, is given by the approximate expression (valid for $m_{\tilde{G}} \ll M_i$[60]):

$$\Omega_{\tilde{G}}^{TP} h^2 \simeq 0.32 \left(\frac{10\ GeV}{m_{\tilde{G}}}\right) \left(\frac{m_{1/2}}{1\ \mathrm{TeV}}\right)^2 \left(\frac{T_R}{10^8\ \mathrm{GeV}}\right) \tag{2}$$

where T_R is the re-heat temperature.

If gravitinos are the LSP, then they can also be produced by decay of the NLSP. In the case of a long-lived neutralino NLSP, the neutralinos will be produced as usual with a thermal relic abundance in the early universe. They will subsequently decay via $\widetilde{Z}_1 \to \gamma\tilde{G},\ Z\tilde{G}$ or $h\tilde{G}$. Thus, the non-thermally produced gravitinos inherit the thermally produced neutralino number density. The total relic abundance is then

$$\Omega_{\tilde{G}} h^2 = \Omega_{\tilde{G}}^{TP} h^2 + \frac{m_{\tilde{G}}}{m_{\widetilde{Z}_1}} \Omega_{\widetilde{Z}_1} h^2. \tag{3}$$

The $\tilde{G}$ from NLSP decay may constitute warm/hot dark matter depending in the $\widetilde{Z}_1 - \tilde{G}$ mass gap, while the thermally produced $\tilde{G}$ will be cold DM[61].

The lifetime for neutralino decay to photon plus gravitino is given by [62],

$$\begin{aligned} \tau(\widetilde{Z}_1 \to \gamma\tilde{G}) &\simeq \frac{48\pi M_P^2}{m_{\widetilde{Z}_1}^3} A^2 \frac{r^2}{(1-r^2)^3(1+3r^2)} \\ &\sim 5.8 \times 10^8\ \mathrm{s} \left(\frac{100\ \mathrm{GeV}}{m_{\widetilde{Z}_1}}\right)^3 \frac{1}{A^2} \frac{r^2}{(1-r^2)^3(1+3r^2)}\ , \end{aligned} \tag{4}$$

where $A = (v_4^{(1)} \cos\theta_W + v_3^{(1)} \sin\theta_W)^{-1}$, with $v_{3,4}^{(1)}$ being the wino and bino components of the $\widetilde{Z}_1$, in the notation of the first item of Ref. [12], M_P is the reduced Planck mass, and $r = m_{\tilde{G}}/m_{\widetilde{Z}_1}$. Similar formulae (with different mixing angle and r-dependence) hold for decays to the gravitino plus a Z or h boson. We see that – except when the gravitino is very much lighter than the neutralino as may be the case in GMSB models with a low SUSY breaking scale – the NLSP decays well after Big Bang nucleosynthesis. Such decays would inject high energy gammas and/or hadrons into the cosmic soup post-nucleosynthesis, which could break up the nuclei, thus conflicting with the successful BBN predictions of Big Bang cosmology. For this reason, the gravitino LSP scenarios usually favor a stau NLSP, since the BBN constraints in this case are much weaker: see, however, Ref. [54] where it is noted that bounds from ^{6}Li abundance constrain the gravitino to be lighter than 10 GeV unless the stau is heavier than 1 TeV.

Before closing this section, we remark that the NLSP could be electrically charged or coloured. It will then be revealed via specialized searches for for quasi-stable, slow-moving particles [63]. More strikingly, it may be possible to trap the very-long-lived ($\tau \sim 10^5 - 10^8$ s) NLSPs produced at high energy colliders, and then search for their subsequent decays [64].

5. Mixed axion/axino dark matter

5.1. Axion dark matter

The axion arises as a by-product of the Peccei-Quinn solution to the strong CP problem[11, 65]. The strong CP problem has its origin in an allowed QCD Lagrangian term,

$$\mathcal{L} \ni \frac{\theta g_s^2}{32\pi^2} G^a_{\mu\nu} \tilde{G}^{a\mu\nu} \;, \tag{5}$$

(here, $G^a_{\mu\nu}$is the gluon field strength tensor and $\tilde{G}^{a\mu\nu}$ its dual) which is both P- and T-violating, and hence CP-violating. When QCD is coupled to the electroweak theory, θ is replaced by $\bar{\theta} \equiv \theta + arg(det\ m_q)$, where m_q is the quark mass matrix. The measured value of the neutron electric dipole moment (EDM) requires $\bar{\theta} \lesssim 10^{-10}$. Explaining the tininess of this Lagrangian term is the strong CP problem.

The Peccei-Quinn solution to the strong CP problem promotes θ to a field in a theory with a global $U(1)$ (Peccei-Quinn or PQ) symmetry, that is broken spontaneously, and by instanton effects. A consequence of the broken PQ symmetry is the existence of a pseudo-Goldstone boson field: the axion $a(x)$[11], which acquires a small mass due to instanton effects. The axion Lagrangian includes the terms

$$\mathcal{L} \ni \frac{1}{2}\partial_\mu a \partial^\mu a + \frac{g^2}{32\pi^2}\frac{a(x)}{f_a/N} G^a_{\mu\nu}\tilde{G}^{a\mu\nu}, \tag{6}$$

where we have introduced the PQ breaking scale f_a and N is the model-dependent color anomaly of order 1. The effective potential for the axion field $V(a(x))$ has its minimum at $\langle a(x)\rangle = -\bar{\theta} f_a/N$, and so the offending $G\tilde{G}$ term essentially vanishes, solving the strong CP problem. An inescapable consequence of this mechanism is the existence of axions with a mass given by,

$$m_a \simeq 6\ \mathrm{eV}\frac{10^6\ \mathrm{GeV}}{f_a/N} \;, \tag{7}$$

and coupled to gluons as in (6), and to photons by an analogous term, with the coupling constant suppressed by the PQ scale, f_a.

Astrophysical limits from cooling of red giant stars and supernova 1987a require $f_a/N \gtrsim 10^9$ GeV, or $m_a \lesssim 3 \times 10^{-3}$ eV. In addition, axions can be produced via various mechanisms in the early universe. Since their lifetime (they decay via $a \to \gamma\gamma$) turns out to be longer than the age of the universe, they can be a good candidate for dark matter in the universe. In SUGRA models, we will be concerned with re-heat temperatures of the universe $T_R \lesssim 10^9$ GeV $< f_a$ (to avoid overproducing gravitinos

in the early universe), the axion production mechanism relevant for us here is just one: production via vacuum mis-alignment[14]. In this mechanism, the axion field $a(x)$ is homogenized by inflation (assumed to occur after the PQ phase transition), and can have any value $\lesssim f_a$ at temperatures $T \gg \Lambda_{QCD}$. As the temperature of the universe drops to the quark-hadron phase transition temperature, the axion potential turns on, and the axion field oscillates about its minimum at $-\bar{\theta} f_a/N$, resulting in the production of *non-relativistic* axions from the nearly homogeneous condensate. This "vacuum mis-alignment" mechanism for axion production thus results in *cold axion dark matter* with a number density,

$$n_a(t) \sim \frac{1}{2} m_a(t) \langle a^2(t) \rangle, \tag{8}$$

where t is the time near the QCD phase transition. Relating the number density to the entropy density allows one to determine the axion relic density today to be

$$\Omega_a h^2 \simeq \frac{1}{4} \left(\frac{6 \times 10^{-6}\ \mathrm{eV}}{m_a} \right)^{7/6}, \tag{9}$$

to within a factor of about three.

The expected axion relic density from vacuum mis-alignment, along with typical error bands, is shown in Fig. 9. It is worth remembering that there is a small chance that $\langle a(t) \rangle \ll f_a$, in which case much lower values of relic density could be obtained. Additional entropy production at $t > t_{QCD}$ can also lower the axion relic abundance. Taking the value of Eq. (9) literally, and comparing to the WMAP5 measured abundance of CDM in the universe, one gets a lower bound $m_a \gtrsim 10^{-5}$ eV on the axion mass, and a corresponding upper bound $f_a/N \lesssim 5 \times 10^{11}$ GeV, on the axion decay constant.

Relic axion search experiments such as ADMX are ongoing. In these experiments, one mounts a super-cooled microwave cavity, and searches for relic axion scattering off microwave photons to yield photons with energy equal to the axion mass. Only recently have experiments begun to probe the theoretically favored regions of f_a/N. A thorough search is expected to continue over the next 5-10 years[66]

5.2. Mixed axion/axino warm and cold dark matter

If we adopt the MSSM as the effective theory below M_{GUT}, and also implement a solution to the strong CP problem via the PQ mechanism, we must introduce not only an axion but also a spin-$\frac{1}{2}$ *axino* $\tilde{a}$ into the theory. The axino mass is very model-dependent, and can be anywhere in the range of keV-GeV[67]. Its coupling is suppressed by the Peccei-Quinn breaking scale f_a, which is constrained to be of order $10^9 - 10^{12}$ GeV: thus, the axino interacts more weakly than a WIMP, but not as weakly as a gravitino. The axion/axino mixture can be a compelling two-component choice for DM in the universe.

Like the gravitino, the axino will likely not be in thermal equilibrium in the post-inflation era. But it can still be produced thermally via particle scattering. Its

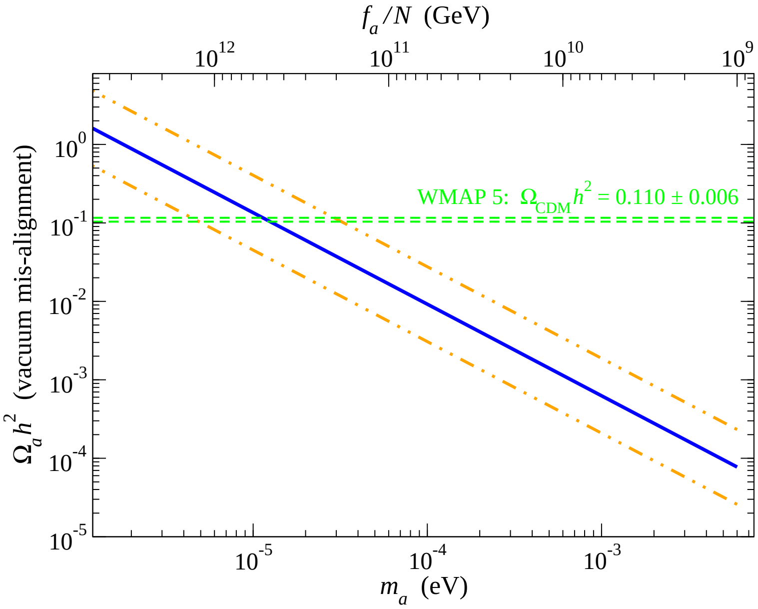

Figure 9. *The expected axion relic density due to vacuum mis-alignment versus m_a (lower scale) and f_a/N (upper scale). The dashed-double-dotted lines show the typical error band on this estimate, while the horizontal band shows the WMAP5 CDM measured abundance. Figure is from Ref. [70].*

abundance via thermal production is given by [16, 68],

$$\Omega_{\tilde a}^{TP}h^2 \simeq 5.5 g_s^6 \log\left(\frac{1.108}{g_s}\right)\left(\frac{10^{11}\ \mathrm{GeV}}{f_a/N}\right)^2\left(\frac{m_{\tilde a}}{100\ \mathrm{MeV}}\right)\left(\frac{T_R}{10^4\ \mathrm{GeV}}\right), \quad (10)$$

where g_s is the strong coupling at the reheating scale. The axino can also be produced non-thermally by NLSP decays, and so will inherit the thermally produced NLSP number density. The total axino abundance is thus given by,

$$\Omega_{\tilde a}h^2 = \Omega_{\tilde a}^{TP}h^2 + \frac{m_{\tilde a}}{m_{NLSP}}\Omega_{\mathrm{NLSP}}h^2. \quad (11)$$

Thermally produced axinos will be CDM for $m_{\tilde a} \gtrsim 0.1$ MeV[16], while the axinos produced in NLSP decay will constitute hot/warm DM for $m_{\tilde a} \lesssim 1$ GeV[61]. Since the PQ scale is considerably lower than the Planck scale, the lifetime for decays such as $\widetilde{Z}_1 \to \gamma\tilde a$ are of order $\sim 0.01 - 1$ sec – just before BBN. Thus, the axino DM scenario is less constrained by BBN than gravitino DM[16].

Note also that if axinos are the CDM of the universe, then models with very large thermal neutralino abundance $\Omega_{\widetilde{Z}_1}h^2 \sim 100 - 1000$ can be readily accommodated, since there is a huge reduction in relic density upon $\widetilde{Z}_1$ decay to the axino. This possibility occurs in models with multi-TeV scalars (and hence a multi-TeV gravitino) and a bino-like $\widetilde{Z}_1$. In this case with very large $m_{\tilde G}$ there is no gravitino problem as long as the re-heat temperature $T_R \sim 10^6 - 10^8$ GeV. This range of T_R is also what is needed to obtain successful *non-thermal* leptogenesis (involving heavy neutrino N production via inflaton decay) [69] along with the correct abundance of axino dark matter [70].

5.2.1. Yukawa-unified SUSY with mixed axion/axino dark matter: Supersymmetric models wherein the $t - b - \tau$ Yukawa couplings are unified at $Q = M_{GUT}$ are highly motivated by simple SUSY GUT models based on the gauge group $SO(10)$. In addition, these models provide a natural explanation for R-parity conservation of renormalizable interactions, and easily accommodate see-saw neutrino masses. Explicit RGE calculations within the MSSM find that Yukawa unification can only occur for very precise soft SUSY breaking boundary conditions [71, 72, 73]: matter scalars have mass $m_{16} \sim 10$ TeV while the GUT scale A_0 terms and Higgs scalars are related as $4m_{16}^2 = 2m_{10}^2 = A_0^2$. With $m_{1/2}$ as small as possible, and $\tan\beta \sim 50$, such models predict first and second generation matter scalars at around the 10 TeV scale, third generation scalars, μ and m_A around a few TeV, gluinos around $350 - 500$ GeV, and a bino-like neutralino around $50 - 90$ GeV [72, 73]. However, these models then predict $\Omega_{\widetilde{Z}_1} h^2 \sim 10^2 - 10^4$, *i.e.* 3-5 orders of magnitude above the measured value.

This seemingly enormous DM relic density can be reconciled with Yukawa-unified SUSY by extending them to include an axion/axino supermultiplet[73] required for the PQ solution to the strong CP problem. In this case, if $m_{\tilde{a}} \sim 1 - 100$ MeV, then the factor $m_{\tilde{a}}/m_{\widetilde{Z}_1}$ suppresses the relic density by the required factor of $10^3 - 10^5$. The axinos produced via neutralino decay would constitute warm DM, but the thermally produced $\tilde{a}$s and the as would constitute cold DM. It is straightforward to find Yukawa-unified models in Ref. [70] where the bulk ($\sim 90\%$)of DM is cold axions and axinos, with a smaller contribution of warm non-thermal axinos. The large value of m_{16}, related to $m_{\tilde{G}}$ under supergravity, allows for a solution to the gravitino problem, and allows for a re-heat temperature in the range $T_R \sim 10^6 - 10^8$ GeV: enough for at least a non-thermal leptogenesis solution to the baryogenesis problem. In this scenario, WIMP DD and ID detection experiments will likely have null results. However, a detectable axion signal may be possible. In addition, with $m_{\tilde{g}} \sim 350-500$ GeV, SUSY signals containing multiple isolated leptons, jets and missing E_T should soon be visible at LHC[74]. In fact, early detection of these light gluinos should be possible via isolated multi-lepton plus multi-jet searches, even before $E_T^{\rm miss}$ becomes a reliable cut variable[75].

6. Summary and Outlook

Science has entered into an era of unprecedented interaction between particle physics, astrophysics and cosmology. It is now certain that the bulk of the matter in the universe is cold and non-luminous: it is not made of any of the known particles, but instead must be made of one or more *new matter states* associated with *physics beyond the SM*. Many new physics theories which address the mechanism behind electroweak symmetry breaking and the stabilization of the electroweak scale naturally contain a stable WIMP particle which may serve as a natural candidate for the observed dark matter. In this review, we have focused our attention on what we believe is the most compelling of these suggestions: *weak scale supersymmetry*, which provides a phenomenologically viable, perturbatively calculable framework with the strong and electroweak gauge interactions

unified in a straightforward way.

SUSY theories with a conserved R-parity always contain a stable particle that in many models has the right properties to be cold dark matter. Within the much-studied mSUGRA model discussed in Sec.2, the neutralino relic density is typically too large over most of the parameter space. There are, however, special regions, mostly at the edge of the $m_0 - m_{1/2}$ plane, where the neutralino annihilation rate in the early universe is enhanced, bringing its predicted *thermal* relic density in accord with the measured CDM density. However, in various extensions of mSUGRA where the underlying scalar/gaugino mass universality is relaxed by the introduction of just one additional parameter, this is no longer the case and, in fact, the entire $m_0 - m_{1/2}$ plane is compatible with the relic density measurement. This calls into question implications of the relic-density-measurement for collider and other SUSY searches from an analysis of just the mSUGRA framework. However, as discussed at the end of Sec. 2, some more robust conclusions applicable to a wide class of gravity-mediated SUSY breaking models may be possible.

We have also examined prospects for direct and indirect detection of DM. An exciting aspect is that a wide variety of models with MHDM have a DD cross section $\sigma_{\rm SI}(\widetilde{Z}_1 p) \gtrsim 10^{-8}$ pb, just an order of magnitude away from current limits, and accessible to the next generation of detectors, *e.g.* Xenon-100/LUX: see Fig. 7. These models may also lead to observable signals in the IceCube experiment, and perhaps, also via other ID experiments. Depending on the underlying theoretical reason for the small value of μ^2 needed for MHDM, there will be different implications for LHC and ILC experiments [39]. The message here is that collider experiments, in tandem with direct and indirect searches, will serve to reveal the underlying physics. A truly unprecedented feature of this program is that if the SUSY WIMP composes the bulk of DM, measurements of the properties of associated sparticles produced at the LHC (possibly complemented by measurements at an electron-positron linear collider) may allow us to independently infer just how much DM there is in the universe, and quantitatively predict what other searches for DM should find. If these predictions turn out to be in agreement with observation, we would have direct evidence that DM mostly consists of just a single component.

While thermal WIMPs provide the simplest and most economic model of DM, it is possible that the DM consists of a particle with interactions that are so weak that it has never been in thermal equilibrium since it was produced during the re-heating phase in the post-inflation era. In this case, the evaluation of the relic density is more complicated and depends on (unknown) details of the thermal history of the Universe. The gravitino, considered in Sec. 4, is a viable DM candidate that has only gravitational interactions. Indeed, the advocates of gravitino DM have argued that the scenario solves some of the potential problems associated with Big Bang nucleosynthesis. In these models, direct and indirect detection experiments should have null results. A long-lived neutralino NLSP will escape a collider detector, resulting in $E_T^{\rm miss}$ events, while a charged (or colored) NLSP will manifest itself as a charged penetrating track of

a slow-moving particle, together with a smoking-gun late-decay signature in dedicated searches[64]. Mixed axion/axino DM, considered in Sec. 5, is another possibility for DM with superweak interactions. An axion signal would be the only DM signature in such a scenario, though as for the gravitino LSP scenario, a charged NLSP would readily reveal itself at the LHC. It has recently been argued that Yukawa-unified models with very light gauginos but very heavy scalars, well beyond the reach of the LHC, augmented by an axion/axino supermultiplet are compatible with the measured value of DM while solving the gravitino problem common to all SUGRA models.

With the LHC scheduled to begin accumulating a significant amount of data starting in 2010, and with many direct and indirect DM detection searches already underway, we are entering what we hope will be a data-driven era of particle physics and cosmology. The new noble liquid detectors for direct DM detection are already competitive with solid-state detectors. Both approaches are beginning to probe highly motivated regions of model parameter space, and very soon should be able to discover (or exclude) DM from a wide class of models with MHDM. As discussed in Sec. 3, there already exist several hints of signals from ID detection experiments. Although it may be likely that these hints turn out to be spurious, the important thing is that these new probes are beginning to explore new regimes and the new, more powerful set-ups such as the FGST should begin to provide precision data very soon. If a definitive WIMP signal emerges from collider and/or direct detection experiments, then it is possible that ID searches will not only corroborate this, but will also serve to map out the galactic DM halo profile. Experiments over the next 10-15 years will likely reveal the identity of dark matter. There is no doubt that the unprecedented synthesis of the physics of the largest and smallest scales observable in nature will make the next two decades very exciting!

Acknowlegements

This research was supported in part by the United States Department of Energy. EKP was supported by the Marie Curie Research and Training Network *UniverseNet* under contract no. MRTN-CT-2006-035863.

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